Renewable and Sustainable Energy Reviews 33 (2014) 752–771

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Grid parity and self-consumption with photovoltaic systems under the present regulatory framework in Spain: The case of the University of Jaén Campus

D.L. Talavera*, J. de la Casa, E. Muñoz-Cerón, G. Almonacid

IDEA Research Group (Investigación y Desarrollo de Energía Solar), University of Jaén Campus las Lagunillas s/n, 23071 Jaén, Spain

ARTICLE INFO

Article history:
Received 2 January 2013
Received in revised form
5 February 2014
Accepted 15 February 2014
Available online 22 March 2014

Keywords:
Grid parity
LCOE
Self-consumption
Net-metering
PV profitability
Economic analysis

ABSTRACT

The cut-off of any subsidy or feed-in tariff that incentives the installation of new renewable energy systems which are close to the grid parity, is a reality in most of the European countries, but in the recent years the grid parity has worsened because of the global economic crisis. In the case of Spain, in addition to the economic problems, the photovoltaic sector has been dramatically damaged through a changeable regulatory framework, an excessive bureaucracy and the inclusion of additional fees or possible back-up tolls that are very prejudicial for the deployment of this sector. Nowadays, the current Spanish legislation mentions the possibility of self-consumption (totally or partially) of the electricity generated by PV or any renewable energy systems but, up to the date of this work, the law that regulates the administrative, technical and economic conditions for the net-metering of the electrical energy produced within the consumer's network, is still under a draft stage. In this paper it is analyzed the case of the University of Jaen, where it has been identified and simulated several PV systems on the roofs and parking lots of the University Campus, and considering the current electrical tariffs (hourly defined for the case of high power and high voltage consumers), it has been done a cost and economic analysis. As a result, it has been obtained an average Levelised Cost of Energy around 0.125 € kWh^{-1}, a discount payback time of 17.5 years or less, a positive Net Present Value and a nominal Internal Rate of Return of 8.48% in the worst case. Beyond that, it has been carried out a sensitivity analysis of the factors that have more influence in the profitability of these systems, like the initial investment cost, the PV electricity yield, additional taxes and the variations in the electricity price market.

Contents

* Corresponding author. Tel.: +34 953 212 809.
E-mail address: dlopez@ujaen.es (D.L. Talavera).

http://dx.doi.org/10.1016/j.rser.2014.02.023
1364-0321

1. Introduction

Several countries have reached the photovoltaic (PV) grid parity as the LCOE of the technology in those places can be compared with their local retail electricity prices in a competitive way. In most of the cases, this parity has been reached without any current subsidy or feed-in tariff incentive, but it has also been necessary a favorable regulatory framework, through net-metering or self-consumption laws [1].

In the case of Spain, although the grid parity is a reality [2], partially thanks to past renewable electricity policies [3], the excessive bureaucracy and the changing and confusing regulatory framework is a pending task in order to avoid barriers for the success of the photovoltaic technology [4].

In December 2011, it was published in Spain the Royal Decree 1699/2011 [5], which regulates the network connection of small power electricity production systems of less than 100 kW. It also mentions the possibility of total or partial self-consumption of the electricity generated by these systems. Later on, the Royal Decree-Law 1/2012, published in January 2012, put off the pre-assignment procedure for the remuneration of renewable systems and it removed the feed-in tariff incentives for the new electricity installations which either use combined heat and power, renewable energy sources or waste [6]. Nowadays, several drafts has been published, which aim is the regulation of the administrative, technical and economic conditions for the self-generation of the electrical energy produced within the consumer´s network [7,8], but according to some authors, the last draft, published in July 2013, contains elements which considerably worsen the economic viability of the PV systems used for self-generation, as the user will have to pay for the energy self-consumed [9].

According to the constantly changing renewable energy laws and the inclusion of the self-consumption concept, prospective owners, big investors or regular householders, are concerned that any further modification of the regulatory framework of the photovoltaic grid-connected systems (PVGCS) may affect the profitability of their investment, because it is outstanding that since 2007 it has been published an average of two different Royal Decree each year derogating past laws and affecting the PV technology in economic terms. Some of these laws even have a retroactive application. Either way, the boom and the bust of the Spanish PV market has to be used as an example and proposal of policy recommendations for solar PV deployment [10,11].

Table 1
Power fee and energy price applied to the University electricity bill (excluding taxes).

Price periods	Energy term	Power term		
	Energy price (€ kWh^{-1})	Annual power fee (€ kW^{-1})	Power contracted (kW)	Annual power cost (€)
P1	0.13818254	38.102134	2,800	106,685.98
P2	0.11282829	19.067559		53,389.17
P3	0.088254	13.954286		39,072
P4	0.080577	13.954286		39,072
P5	0.077474	13.954286		39,072
P6	0.059444	6.366846		17,827.17

In this paper an economic and cost analysis of several PVGCS on buildings has been carried out similar to other studies made in Germany or Italy [12], but in this case we have adapted it to the last Spanish legislation because the examples found in Spain [13] are referred to a really different legislative scenario, even though the paper consulted was written in the last semester of 2012, and it also differs in the technical solution because in their study they analyzed household facilities and we have particularized this study to a public institution, the University of Jaén in Southern Spain, where the disposal of free space and high levels of radiations make this location an ideal place for the installation of PV systems.

Firstly, it has been estimated the PV potential of some buildings and parking lots of the campus as a previous step to undertake the cost and economic analysis, where it has been assumed that all the PV electricity generated is for the University instant self-consumption and the electricity unitary price, in € kWh^{-1}, is the same as the unitary electricity price paid by the University to the Electrical Company.

In the estimation of the self-consumed electricity unitary price, we have considered the particularities of the University as a high power consumer. Most of the households consumers, which have a low-medium power contracted, are gathered in the Last Resort Tariff (TUR in the Spanish acronym), which regulates the price that the consumer must pay to the electricity company. In this tariff, both the power fee and the energy price are set by the Government [14]. This is not the case of the University of Jaen, a high power and a high voltage consumer, where the power fee is fixed by the Ministry of Industry, Energy and Tourism but the energy price is contracted freely between the University and the supplier. Table 1 shows the power fee and the energy price paid by the University since August 3rd 2013, when it was introduced the Ministerial Order IET/1491/2013 [15].

According to the energy bill payment, with the present Spanish regulatory framework, there are defined several consumption profiles and tariffs [16]. In our case, tariff 6.1, there are six different price periods (P1–P6), according to the definition of electrical seasons and type of days, each one with a certain number of hours attached. Table 2 gathers the hourly price profile from Monday to Friday, excluding public holidays, for each month of the year.

If the same study is done in a household facility, the use of just a single electrical tariff would have simplify the analysis, but the novelty in the methodology used in this paper where we want to carry out an accurate and complete profitability analysis, makes us to correlate the consumption and energy generation profiles with the hourly price periods defined in our energy bill for each month of the year.

The methods for the economic analysis used in this paper are the net present value (NPV), the discounted payback time (DPBT) and the internal rate of return (IRR), but the equations used have been modified so we can adapt the analysis under different hourly electricity prices. The PV electricity cost production has been estimated through the concept Levelised Cost of Electricity (LCOE) in order to compare the photovoltaic technology with other sources of electricity [17].

The main aim of the paper is to assess the feasibility of these systems, proving that the grid parity paradigm is possible and profitable, and also to contribute to other future works in other countries or, for example, in the smart grid research, which it is also a trending topic in the European Union Policy [18,19]. In order

Table 2
Hourly profile of the price periods from Monday to Friday, excluding public holidays [16].

Month	Hours of the day																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
January	P6	P6	P6	P6	P6	P6	P6	P6	P2	P2	P1	P1	P1	P2	P2	P2	P2	P2	P1	P1	P1	P2	P2	P2
February	P6	P6	P6	P6	P6	P6	P6	P6	P2	P2	P1	P1	P1	P2	P2	P2	P2	P2	P1	P1	P1	P2	P2	P2
March	P6	P6	P6	P6	P6	P6	P6	P6	P4	P4	P4	P4	P4	P4	P4	P4	P3	P3	P3	P3	P3	P3	P4	P4
April	P6	P6	P6	P6	P6	P6	P6	P6	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5
May	P6	P6	P6	P6	P6	P6	P6	P6	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5
June																								
1–15	P6	P6	P6	P6	P6	P6	P6	P6	P4	P3	P3	P3	P3	P3	P3	P4	P4	P4	P4	P4	P4	P4	P4	P4
15–30	P6	P6	P6	P6	P6	P6	P6	P6	P2	P2	P2	P1	P1	P1	P1	P1	P1	P1	P1	P2	P2	P2	P2	P2
July	P6	P6	P6	P6	P6	P6	P6	P6	P2	P2	P2	P1	P1	P1	P1	P1	P1	P1	P1	P2	P2	P2	P2	P2
August	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6
September	P6	P6	P6	P6	P6	P6	P6	P6	P4	P3	P3	P3	P3	P3	P3	P4	P4	P4	P4	P4	P4	P4	P4	P4
October	P6	P6	P6	P6	P6	P6	P6	P6	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5
November	P6	P6	P6	P6	P6	P6	P6	P6	P4	P4	P4	P4	P4	P4	P4	P4	P3	P3	P3	P3	P3	P3	P4	P4
December	P6	P6	P6	P6	P6	P6	P6	P6	P2	P2	P1	P1	P1	P2	P2	P2	P2	P2	P1	P1	P1	P2	P2	P2

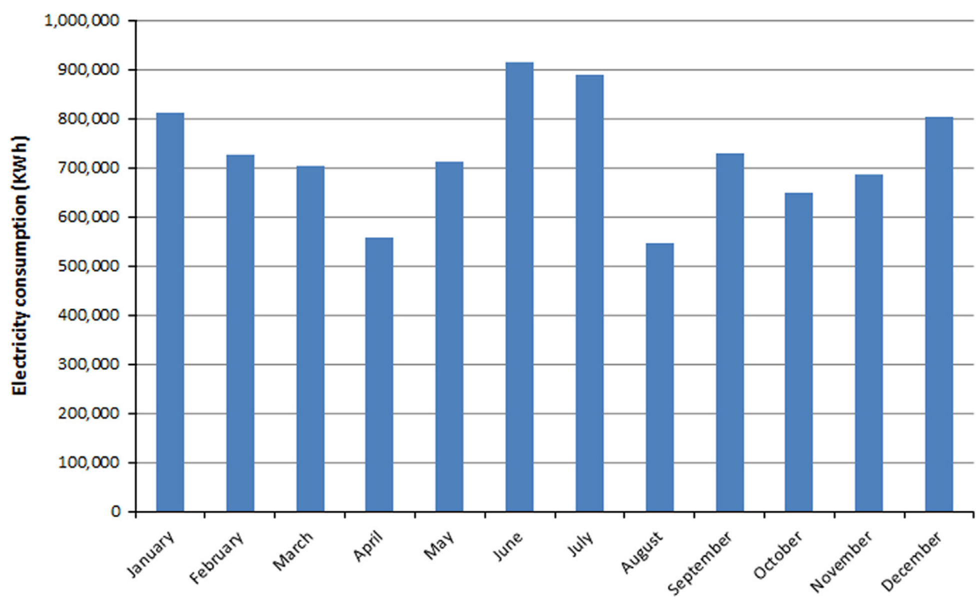

Fig. 1. Average electricity consumption.

to facilitate the extrapolation of this work to other similar self-consumption scenarios, we have carried out a sensitivity analysis of the factors that have more influence in the profitability of these systems.

2. Consumption, PV generation and cost analysis

It is necessary to study the present electrical consumption profiles of the University to compare them with the generation of solar energy that might take place in the potential PV areas that will be analyzed in this paper. This comparison will allow us, after the proper cost analysis, to deliberate about the feasibility of installing these types of systems within the present Spanish regulatory framework.

2.1. Electricity consumption

It is relatively simple to measure the overall electricity consumption of the Campus, but we want to make a deep cost analysis, so it is more suitable to adapt these consumption profiles to the retail price of the electricity paid by the University shown in Table 1.

The electricity consumption for each month, which is an average for the last 3 years (Fig. 1), together with its hourly division, is not enough for the purposes of this study. It is more interesting to analyze this hourly profile depending on the following classification: (1) Working days (from Monday to Friday) and (2) public holidays, Saturdays or Sundays. This last group always has a price period P6. The University is an educational institution, so into the classification of working days, we have to extract those corresponding to non-school days. Normally, the difference between school and the rest of working days are due to holidays at Christmas, Easter and the month of August, when most of the facilities of the University are closed. In our energy analysis we have divided these two terms to distinguish all the possibilities that we may have in the consumption profiles. The daily electricity consumed at the University under this classification can be observed from Figs. 2 to 4.

2.2. Energy generation with photovoltaic technology

In previous research papers it was studied the PV potential of the University of Jaen campus and the large integration of these systems in the University facilities [20–22].

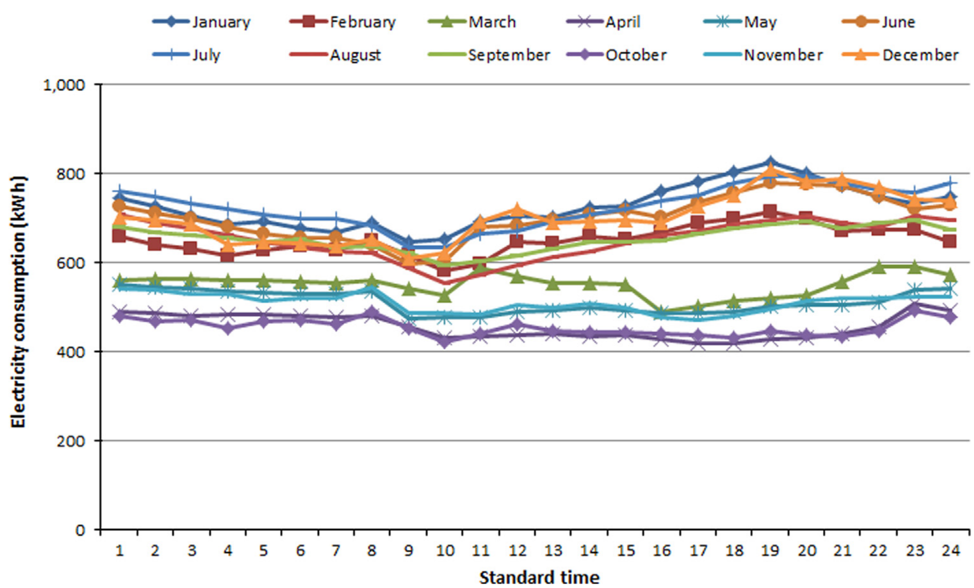

Fig. 2. Hourly electricity consumption of an average Saturday, Sunday and public holiday day.

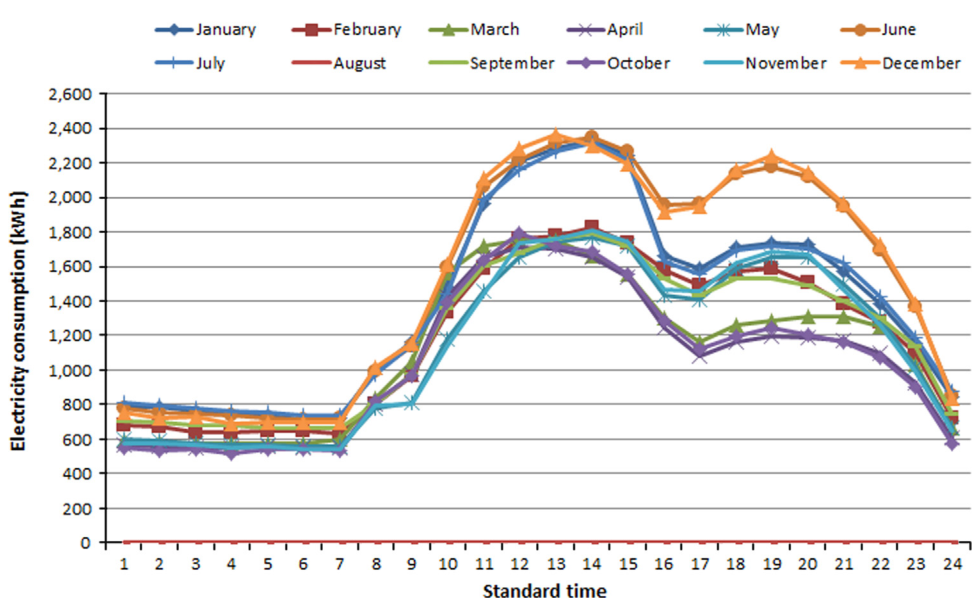

Fig. 3. Hourly electricity consumption of an average school working day.

The present Spanish regulatory framework, RD 1699/2011, and the draft of the future net metering law, whose technical aspects are expected to remain the same in the definite document, establishes a limitation in the PV power to be installed of 100 kW maximum, so in order to adapt the locations identified in this study to the power requirement, we have divided the PV systems into this power limit mentioned.

Fig. 5 shows the identification of the main areas, where it was added a new location (Area 4) when compared to the previous studies mentioned, because the N–W parking lot was recently built. The PV power division of these areas are summarized in Table 3, where it is included the geographical characteristics and energy yield of each possible system. The azimuth and tilt detailed in each system corresponds either to the optimum case for each location or with the purpose of making a good building integrated photovoltaic system using the present building structures. The PV systems located on the rooftops can be handled in order to obtain azimuth 0° and the best tilt angle for the Jaén latitude, but in the case of the parking lots, they cannot be randomly oriented or tilted because the aim in these cases is to maximize the existing structure.

2.2.1. *Theoretical model for the estimation of the energy generated*

The methodology used for the estimation of the energy that could produce each PV system identified previously needs 12 values of radiation, that correspond to the monthly average values of horizontal daily global radiation ($H_{dm}(0)$). Additionally, it has been used 12 monthly average values corresponding to the maximum daily temperature (T_{aMdm}) and the minimum daily values too (T_{amdm}).

From this reduced set of data, there are procedures for the estimation of the temporary evolution of the incident irradiance on the generators' surface and so does the temperature, with fixed time intervals from a "representative day" for each month of the year [23,24].

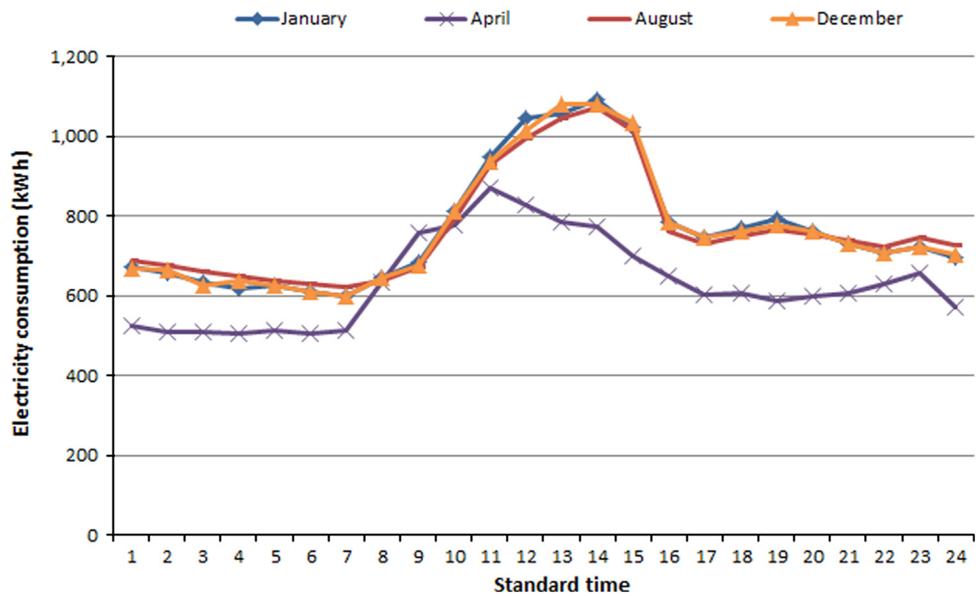

Fig. 4. Hourly electricity consumption of an average non-school working day.

Fig. 5. Identification of potential PV areas.
Source: Adapted from Google Maps™.

Subsequently, it has been considered that every day from the same month has an identical temporary evolution, related to those environmental parameters, than its "representative day". The estimations for the operational behavior of the PVGCS using this methodology are reliable and the differences are below 3% if it is compared with other methods more resolute [25].

The typical or representative day is an hypothetic day located in the middle of the month under consideration, in which it is assumed that horizontal global radiation value ($H_{dr}(0)$) matches the monthly average value of horizontal daily global ($H_{dm}(0)$) for that month. The maximum and minimum temperatures of this representative day (T_{aMdr} and T_{amdr}) match the maximum and minimum monthly average value of daily temperature.

The monthly average radiation and temperature data used in this paper have been obtained thanks to the free service offered by the NASA research center in Langley, where these parameters have been measured over the last 10 years [26]. We could have used other data sources, but for the purposes of this paper the results do not vary significantly.

From these values identified, the calculation process of the useful irradiance falling on the module's surface and the instant ambient temperature, it is done by means of the theoretical procedure described below:

- Calculation of the horizontal beam and diffuse monthly irradiation using the expressions proposed by Liu and Jordan [27] and the correlations obtained by Page [28].
- Calculation of the irradiance from daily irradiation, according to the method proposed by Whillier [29].
- Calculation of the effective irradiance within the PV generator surface following the model proposed by Pérez for the diffuse component on an arbitrary oriented surface [30] and the model of Martín–Ruíz [31] that calculates the energy losses due to the incidence angle and considering, in our case, that the level of dirt on the generator is low-medium.
- Finally, calculation of the ambient temperature assuming that it changes following two semi-cycles of two cosine functions [32].

Once the operating conditions of the photovoltaic systems are determined, the maximum power generated by each one is calculated using the Osterwald method [33], which allows the determination of the PV power under certain incident irradiance

Table 3
PV potential areas.

Potential areas	Location	PV power (kWp)	Azimuth (°)	Inclination (°)	Annual yield (kWh kWp^{-1})
Area I	Building 1	101	0	30	1,418
	S Parking lot 1	110			
	S Parking lot 2	110	40	8	1,239
	S Parking lot 3	110			
Area II	Building 2	91	0	30	1,418
	N Parking lot 1	100			
	N Parking lot 2	100	42	8	1,237
	N Parking lot 3	100			
	N Parking lot 4	98			
Area III	Pergola	110	25	12	1,291
	Building 3	74	0	30	1,418
Area IV	N-W Parking lot	105	39	8	1,240
Total		1,209			1,282

Table 4
Losses considered in the energy estimation method.

	(%)
DC losses	
DC wiring losses	1.5
Mismatch losses	1.5
Nominal power reduction	1
Inverter losses	
Maximum power point tracking losses	1
DC/AC conversion efficiency	96
Other losses	
AC wiring losses	1
Maintenance and breakdown stops	3
Shadowing	4

and cell temperature. This method has been proved by Fuentes to be simple but with small error in the prediction of the maximum power [34]. Thus, the maximum power is calculated using the following equation, where there is a minimum irradiance threshold of 100 W m^{-2} for its reliable use:

$$P_M = P_{M,STC}\ (\mathrm{W}) + \frac{G(\alpha,\beta)(\mathrm{W\ m^{-2}})}{1000\ \ (\mathrm{W\ m^{-2}})}[1+\gamma(^\circ\mathrm{C}^{-1})(T_C\ (^\circ\mathrm{C}) - 25\ (^\circ\mathrm{C}))] \tag{1}$$

In the equation described above, it has been calculated the cell temperature with the following expression, where it has been used the NOCT parameter, which it is specified in the manufacturer's datasheet:

$$T_C\ (^\circ\mathrm{C}) = T_A\ (^\circ\mathrm{C}) + G(\alpha,\beta)(\mathrm{W\ m^{-2}})\frac{\mathrm{NOCT}\ (^\circ\mathrm{C}) - 20\ (20\ ^\circ\mathrm{C})}{800\ (\mathrm{W\ m^{-2}})} \tag{2}$$

The real AC power generated by these systems is influenced not only by meteorological parameters, but it also has to be considered different sources of losses that are inherent to these sorts of systems. In Table 4 it is summarized the losses considered for our energy analysis, according to the characteristics of the PV potential system locations and the wide experience with real PV measurements that the IDEA Solar Research group has obtained all along its research developed and published [35,36].

2.2.2. Generation-consumption results and comparison

The energy yield for each system (see Table 3) has been estimated with the method described previously, but for the purposes of our study it is necessary to adapt this energy generated to the hourly consumption profiles, so it will allow us to identify the energy excesses and deficits of our PV systems alongside a certain period of time.

The hourly solar electricity generation profile on the typical day for each month is shown in Fig. 6, where it has been considered all the potential PV locations at the University.

In this paper, it has been defined the term Net Electricity Generation (NET), which stands for the difference between the PV energy generations minus the consumptions profiles described in Section 2.1. If the hourly electricity consumption data from Fig. 3 is compared against the energy generation profile, it is shown the NET data for an average school working day (see Fig. 7). In this situation, there will be a negative energy balance in every hour of the day, which means that it is necessary to consume electricity from the main electricity grid in order to meet the electricity needs of the University. A similar result is obtained for a non-school working day (see Fig. 8), but in this case this deficit is less significant as the previous one. Therefore, it can be deduced that all the energy produced within any working day (either school or non-school day) is completely used for self-consumption at the facilities of the University.

On the other hand, if Saturdays, Sundays and public holidays are analyzed (see Fig. 9), it is outstanding that the excess in the energy generated is around 32,785 kWh year^{-1}. This data is calculated through the daily integration of the area covered under the positive NET data curves. This integration extended for every day of each month during a year give us this energy excess, which means that the University would be injecting electricity into the grid. For our study, we have assumed that this energy excess will be injected into the public electricity net at no cost, because we have declined any sort of remuneration or compensation to the producer (the University). According to current renewable energy laws, we won't need to pay any access fee for this energy injected. For the purposes of our job, we will not take into account this energy excess for the economic analysis.

This unused electricity in our facilities may be easily absorbed within a small area surrounding the University Campus as it can be observed in Fig. 10. This fact comes to reinforce the feasibility of distributed generation concept, thus reducing the losses of the power lines.

If the generation and consumption profiles are analyzed and compared throughout a year, we obtain the results summarized in Table 5. The amount of electricity, in energy terms, saved in the University bill as a consequence of the self-consumed electricity goes up to 17.4% annually, varying this term depending on the type of day selected. A summary of the energy production in each period is shown in Table 6.

Although the University savings in the electricity consumption, it does not mean that it necessarily turns into economic savings or even that these PV systems are profitable in the mid-long term, so an electricity cost production analysis must

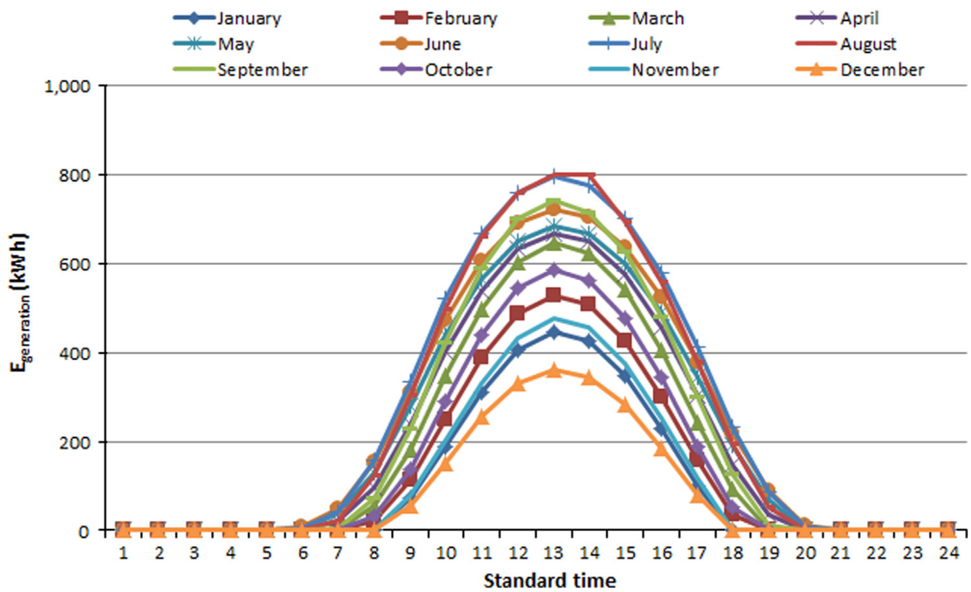

Fig. 6. Hourly solar electricity generation profile.

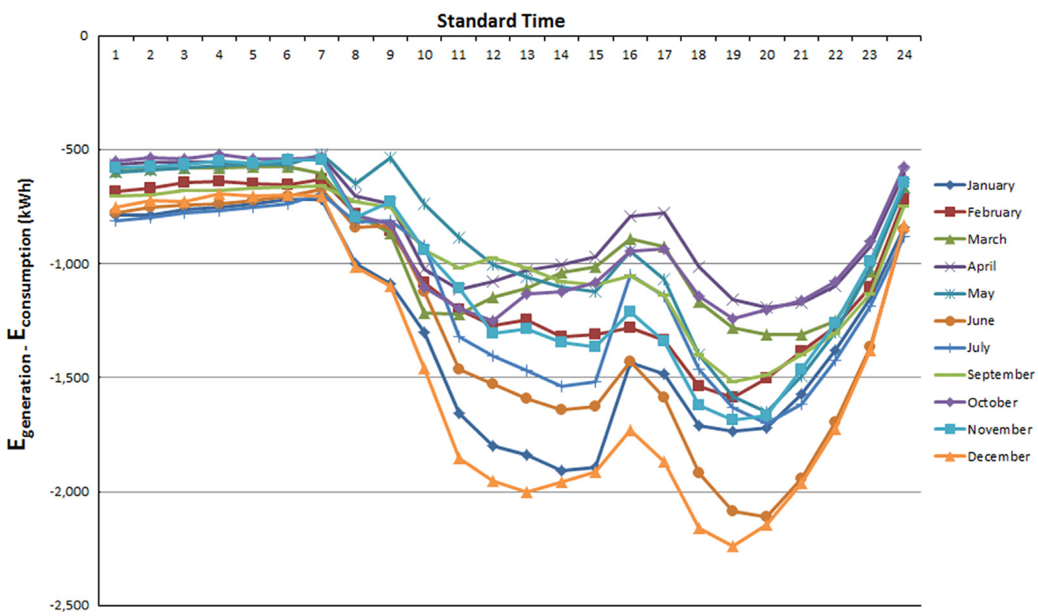

Fig. 7. Net electricity generation in an average school working day.

be carried out prior to assess the suitability and viability of these sorts of systems.

2.3. Electricity cost generation

The main issue in this analysis is related with the cost of a PV system, that it should be recovered by the annual energy produced, so for this purpose it is necessary to define the cost, in current monetary units, of a kWh of electricity produced by a certain PV system throughout its whole operational years [37].

In this case, it is used the Levelised Cost of Electricity (LCOE) term, which value is constant over the whole lifetime of the system. The following expression is used for its calculation:

$$LCOE = \frac{LCC_{USP}}{\sum_{i=1}^{N} \frac{E_{PV}}{(1+d)^i}} \tag{3}$$

For the estimation of LCOE it has been considered all the cumulated system costs and the energy generated over its lifetime so, according to the previous equation, E_{PV} is the annual PV electricity yield (kWh) and d is the nominal discount rate. The real discount rate (d_r) is derived from the latter by Eq. (4), where g is the annual inflation rate.

$$d_r = \frac{d-g}{1+g} \tag{4}$$

LCC_{USP} is the life-cycle cost (€) of the system from the user's standpoint and it is calculated, in Eq. (5), with the sum of the present worth of the initial investment cost of the PV system ($PW[PV_{IN}]$) and the present worth of the operation and maintenance cost ($PW[PV_{OM}(N)]$) associated with the PV technology [38].

$$LCC_{USP} = PW[PV_{IN}] + PW[PV_{OM}(N)] \tag{5}$$

The initial investment cost, PV_{IN}, considering an absence of any subsidy, is supposed to be paid by the owner. This amount either

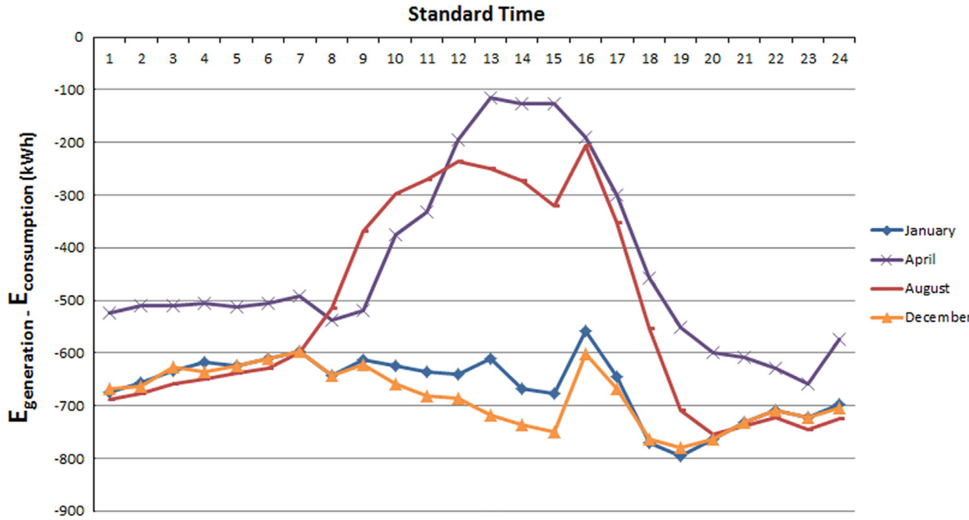

Fig. 8. Net electricity generation in an average non-school working day.

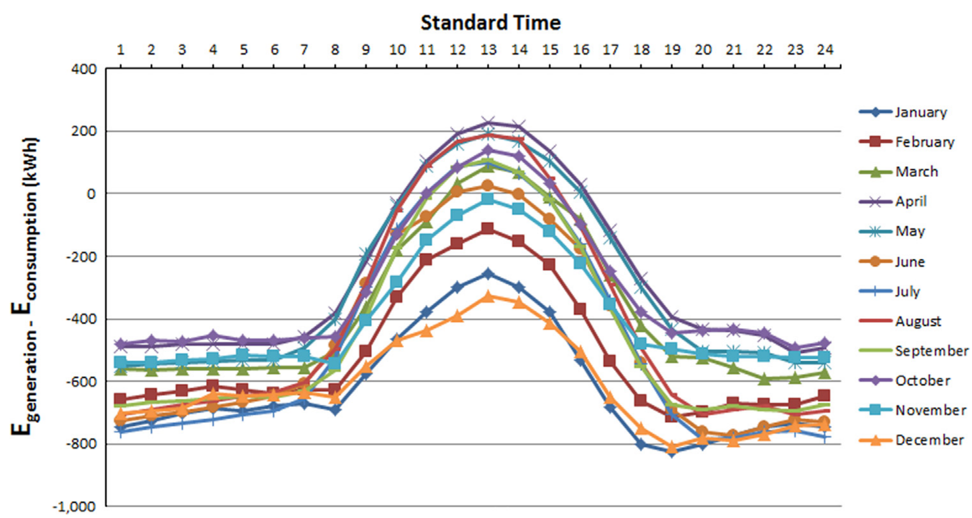

Fig. 9. Net electricity generation in an average Saturday, Sunday and public holiday day.

Fig. 10. University of Jaen surrounded by large consumption centers.
Source: Adapted from Bing Maps™.

Table 5
Energy analysis summary.

Parameter	Working school days	Working non-school days	Saturdays, Sundays and public holidays	Annual
Electricity consumption(kWh/year)	6,429,312	613,408	1,682,187	8,724,908
Self-consumed electricity from the PV systems proposed (kWh/year)	905,295	165,295	446,929	1,517,519
PV electricity injected into the grid (kWh/year)	0	0	32,785	32,785
Savings in electricity (%)	14.1	26.9	26.5	17.4

Table 6
Summary of the energy production in each period.

Month	Periods						Monthly production (kWh)	Monthly self-consumption (kWh)	Monthly Excess (kWh)
	P1	P2	P3	P4	P5	P6			
January	23,272	27,190	0	0	0	27,754	78,216	78,216	0
February	29,441	37,551	0	0	0	26,123	93,115	93,115	0
March	0	0	7,378	84,593	0	39,331	131,301	129,571	1,730
April	0	0	0	0	88,230	54,611	142,841	132,875	9,966
May	0	0	0	0	109,497	50,093	159,591	153,108	6,483
June (1–15)	0	0	40,213	16,107	0	27,297	83,618	83,481	137
June (15–30)	41,618	14,702	0	0	0	27,297	83,618	83,481	137
July	95,418	33,653	0	0	0	59,049	188,121	185,794	2,327
August	0	0	0	0	0	180,997	180,997	175,017	5,980
September	0	0	75,828	22,950	0	51,708	150,486	147,856	2,630
October	0	0	0	0	79,635	33,558	113,192	109,795	3,397
November	0	0	2,429	54,815	0	24,533	81,778	81,778	0
December	17,996	20,881	0	0	0	24,554	63,431	63,431	0
Annual production in each period (kWh)	207,745	133,977	125,848	178,465	277,362	626,906			
Annual (kWh)							1,550,304	1,517,519	32,785

may be financed partly with a low-interest loan or may be financed (the rest of the initial investment cost) by using own capital (PV_{OC}). In the first case, a part of this amount is borrowed at an annual loan interest i_l and loan term N_l (years), while the remaining part, financed with own capital, has an annual retribution in form of dividends (d_i) and it is amortized at the end of the life-cycle of the system. Considering these terms, where it has been defined the factor $q=1/(1+d)$, the present worth of the initial investment cost of the PV system $PW[PV_{IN}]$ can be expressed as it follows:

$$PW[PVIN]=\left((PV_{IN}-PV_{OC})i_l\frac{(1+i_l)^{N_l}}{(1+i_l)^{N_l}-1}\frac{q(1-q^{N_l})}{1-q}\right)+\left((d_i\ PV_{OC})\frac{q(1-q^N)}{1-q}+PV_{OC}\ q^N\right) \quad (6)$$

where the value of d=WACC, the weighted average cost of capital (WACC). This parameter refers to the cost that the owner of the PV system must pay for using the available financial resources to finance the initial investment cost.

Concerning the life-cycle operation and maintenance cost, it has been defined an annual operation and maintenance cost, PV_{AOM}, and an annual escalation rate (ε_{PVOM}) of the operation and maintenance cost of the PV system, so $PW[PV_{OM}(N)]$ may be written as

$$PW[PV_{OM}(N)]=\left(PV_{AOM}\frac{K_{PV}(1-K_{PV}{}^N)}{1-K_{PV}}\right),$$
$$\text{where } K_{PV}=(1+\varepsilon_{PVOM})/(1+d) \quad (7)$$

2.3.1. Estimation of parameters

The most sensitive parameter with influence in the variation of the LCOE is the initial investment cost per kWp of PV grid-connected system. The variability of this parameter is related to the country and the scenarios assumed as it can be observed in some international reports. In the case of the analysis carried out by the EurObserv'ER database barometer, it defined a price of 2,082 € kWp^{-1} for roof PV systems installed in Germany in the last quarter of 2011 [39], meanwhile other sources estimates a scenario for 2015 of 2,280-2,770 US$ kWp^{-1}, that it may be translated into a range of 1,700–2,350 € kWp^{-1} depending on the US$–€ differences [40].

In order to identify the evolution of the installed PV system price in Spain, we have compiled economic data from 2006 to 2010, where the price of installed PV systems ranged from 2.4–2.7 € Wp^{-1} [41–45]. There is no data available for Spain in the last IEA report, referred to 2011 [46], so according to the slowdown of the Spanish PV industry, the economic crisis in the country and some PV Spanish economic reports and news [47], we have assumed that in the last quarter of 2012, the prices experienced a decrease of 32% when compared to 2010, so the initial investment per kWp in Spain ranges from 1.7 to 1.9 € Wp^{-1}, including VAT. In Fig. 11 it is represented this evolution for Spain, where the prices for the years 2011 and 2012 fit our estimations.

In this paper, the amount of money to be paid by the owner, PV_{IN}, is considered to be mixed financed. On the one hand, 80% of this amount is assumed to be borrowed at an annual loan interest i_l=6% and a loan term N_l=15 years, while the remaining part (20% of PV_{IN}) is defrayed with own capital PV_{OC}, so that the annual retribution is given in form of dividends d_i=5% and amortized at the end of the life-cycle of the system [48].

The annual inflation rate g=2.8% has been defined according to some historical average data (from 2001 to 2010) for Spain [49,50], and the annual escalation rate of the operation and maintenance cost of a PV system is assumed to be equal to the value of the annual inflation rate, so ε_{PVOM}=2.8%. The discount rate (d) is assumed equal to the weighted average cost of capital (WACC) in

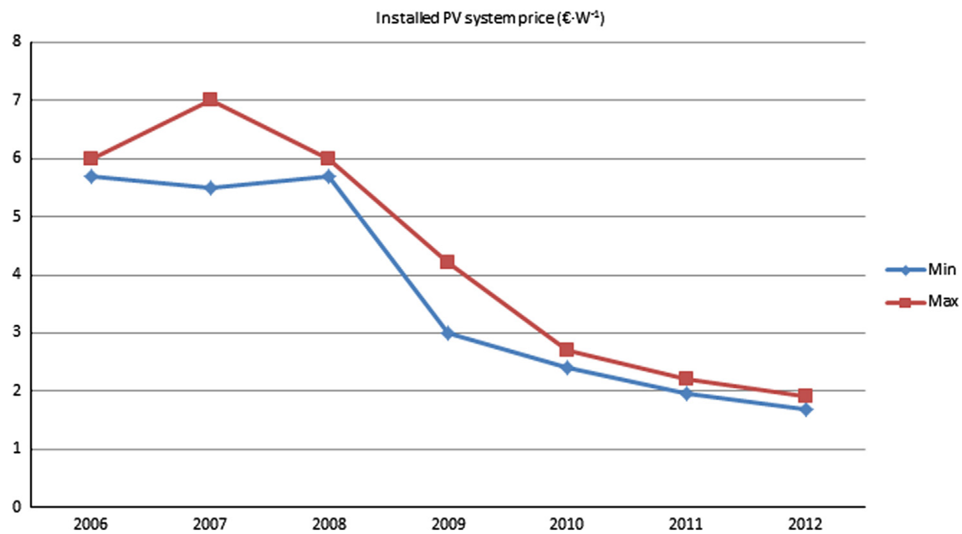

Fig. 11. Price evolution in Spain for installed PV systems.

Table 7
Parameters considered in the PV systems for the cost analysis.

Location	Factors							
	$[PV_{IN}]_{kWp}$ (€ kWp^{-1})	PV_{OM} (€/years)	ε_{PVOM} (%)	Financial			g (%)	d_g (%)
				Low-interest loan (80% of PV_{IN})		Own Capital (20% of PV_{IN})		
				i_l (%)	N_l (years)	di (%)		
Building 1	1,900							
S. Parking lot 1	1,700							
S. Parking lot 2	1,700							
S. Parking lot 3	1,700							
Building 2	1,900							
N. Parking lot 1	1,700							
N. Parking lot 2	1,700	1% $[PV_{IN}]$	2.8	6	15	5	2.8	0.8
N. Parking lot 3	1,700							
N. Parking lot 4	1,700							
Pergola	1,800							
Building 3	1,900							
N–W Parking lot	1,700							

order to calculate the LCOE. The WACC refers to the cost that the owner of the PVGCS must pay for using the available financial resources to finance the initial investment cost. This WACC will vary depending on how the financial resources are chosen to finance the initial investment cost, and in our case the WACC is equal to 5.6%.

The annual operation and maintenance cost will represent a 1% of the initial investment cost [51], and it has been considered an annual degradation rate (d_g) of the power of the PVGCS equal to 0.8%, which lies within the range defined by some photovoltaic experts [52]. All these parameters, referred to the locations identified for our study, are summarized in Table 7.

Table 8
LCOE for each PV system proposed.

Location	LCOE (€ kWh^{-1})
Building 1	0.12333
S Parking lot 1	
S Parking lot 2	0.12629
S Parking lot 3	
Building 2	0.12333
N Parking lot 1	
N Parking lot 2	0.12650
N Parking lot 3	
N Parking lot 4	
Pergola	0.12834
Building 3	0.12333
N–W Parking lot	0.12619

2.3.2. Cost analysis results

The results obtained will be determinant for the profitability analysis that we will develop in further sections, and according to the data obtained (see Table 8), the LCOE of all systems swings around 0.125 € kWh^{-1}, so the predictions and reports for the grid parity in the Spanish net are confirmed [1].

Obviously, the LCOE is very sensitive to variations of some parameters used in its calculation so it is interesting to foresee several scenarios. First of all, we have supposed a fixed price per Wp installed, according to the literature found, but this variable may have important fluctuations. With the purpose to facilitate the extrapolation of these analysis data to other countries with similar radiation levels but higher or lower system prices, in Fig. 12 it is represented a sensitive analysis of the LCOE regarding the

initial investment cost variations, where the worst and best scenarios studied differ in a $\pm 25\%$ of the cost per kWp defined in the base case. These variations suppose a range in the LCOE term around 0.16 to 0.092 € kWh^{-1} in the best scenario possible. Following the decrease in the PV system prices, is more probable to achieve the best scenarios prices in the short-mid-term.

If all the predictions agree with the decreasing tendency of prices, it is more interesting to represent the variation of LCOE regarding the PV electricity yield variations. The estimations in the annual energy yield are dependent on many variables, starting with the efficiency of the PV modules used, the optimum design of the PV system, the differences among the solar radiation databases and the location of the systems. In the South of Spain there is a favorable sunny weather for the photovoltaic technology, but in similar University facilities from northerner locations, the availability of these levels of radiation will be lower. In Fig. 13 it is shown a LCOE sensitivity analysis regarding the PV electricity yield variations, where it has been considered scenarios of $\pm 25\%$ differing from the base case.

Besides the LCOE, it is interesting the estimation of self-consumed electricity (€/year) and calculate the percentage of savings in the electric bill that the University may have if all the

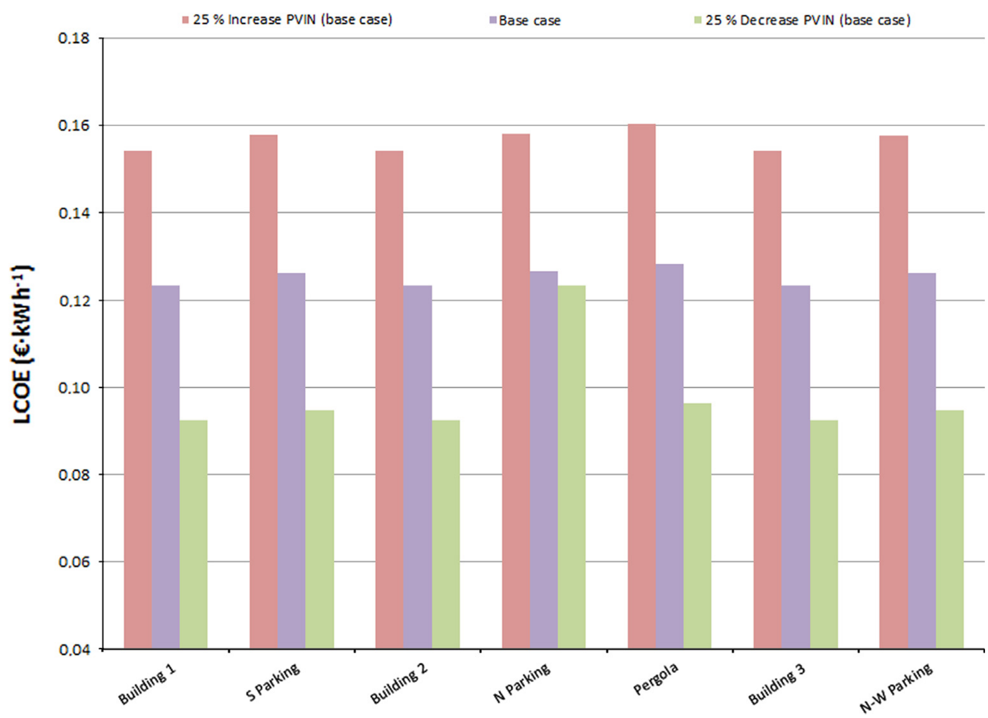

Fig. 12. LCOE sensitivity analysis regarding the initial investment cost variations.

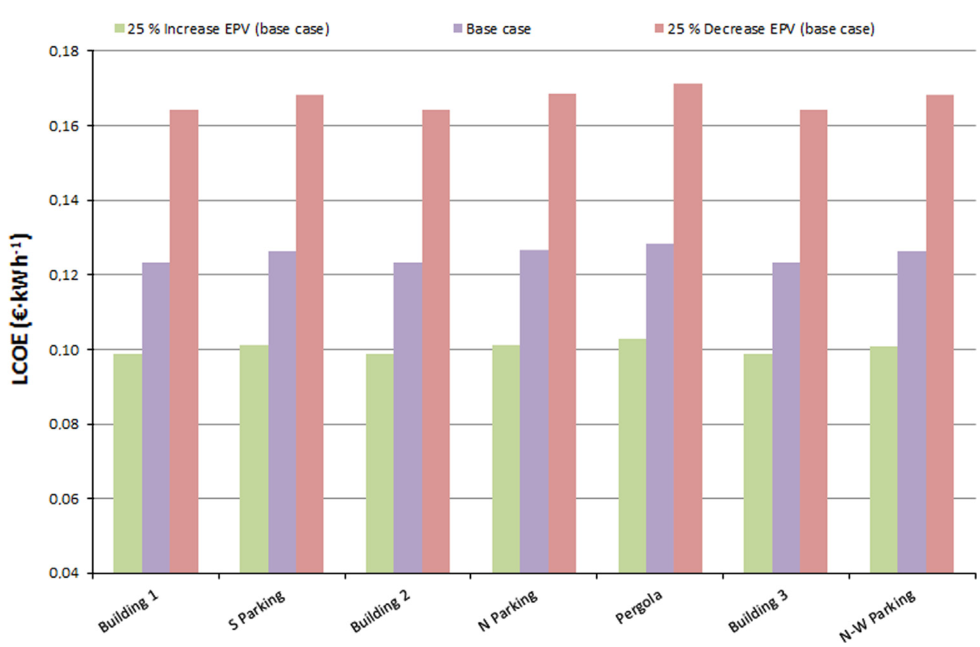

Fig. 13. LCOE sensitivity analysis regarding the PV electricity yield variations.

Table 9
Cost analysis summary.

Parameter	Working school days	Working non-school days	Saturdays, Sundays and public holidays	Annual
Cost of the electricity Consumption (€€/year)	721,444	53,102	120,896	895,442
Self-consumed electricity savings from the PV systems proposed (€/year)	106,743	13,692	29,944	150,364
Savings in the electric bill (%)	14.80	25.78	24.77	16.79

proposed PV systems were installed. A cost analysis summary is shown in Table 9, where it is observed a 16.79% of savings in the electric bill.

3. Profitability analysis

The savings in the electricity consumption or in the electric bill can mislead the regular electricity consumer, as one may think that these savings are translated into the feasibility of the system. Nevertheless, it has to be done an economic analysis that asses the profitability of the investment, regardless the electric bill may appear a reduction in the money to be paid to the company.

In this paper it has been used the most common profitability indices: the Net Present Value (NPV), the Discounted Payback Time (DPBT) and the Internal Rate of Return (IRR). The calculation procedures are similar to those presented in several papers [53] but with a slightly improvement, because the present worth of the cash inflows from the system (PW[CIF(N)]) considers different items, such as a PV power loss factor, the electricity tariff periods (P1–P6) and it differentiates the self-consumed energy from the one injected to the grid. Therefore, the Net Present Value may be written, in general, as follows:

$$\mathrm{NPV} = \mathrm{PW}[\mathrm{CIF}(N)] - \mathrm{LCC}_{USP} \quad (8)$$

In those countries where there is a net or bill metering, part of the annual PV electricity generated (E_{PVs}, in kWh) is used for self-consumption at a given price (p_s, in € kWh^{-1}), which is set at the retail price of the market, while the remaining annual electricity generation (E_{PVg}, in kWh) is fed into the grid, which may be compensated at a different price than the retail price of the market (p_g, in € kWh^{-1}), so PW[CIF(N)] may be written as

$$\mathrm{PW}[\mathrm{CIF}(N)] = p_s E_{PVs} \frac{K_{p_s}(1-K_{p_s}^N)}{1-K_{ps}} + p_g E_{PVg} \frac{K_{pg}(1-K_{pg}^N)}{1-K_{pg}} \quad (9)$$

In the previous equation, N (years) is the serviceable life of the system. K_{ps} and K_{pg} are two factors related to the increase rate of the electricity price and decrease rate of the power. They are expressed as follows:

$$K_{ps} = (1+\varepsilon_{ps})(1-\varepsilon_{pl})/(1+d) \quad (10)$$

$$K_{pg} = (1+\varepsilon_{pg})(1-\varepsilon_{pl})/(1+d) \quad (11)$$

In Eqs. (10) and (11), ε_{ps} and ε_{pg} stand for the annual increase rate of the electricity price that is saved and injected into the grid respectively, while ε_{pl} is a factor for the annual decrease rate of the power of the grid-connected PV system.

We are analyzing a specific location, The University of Jaén, where the electricity utility applies several tariffs according to hourly profiles as it was described in previous sections, so Eq. (9) must be rearranged to take into account these periods (p):

$$\mathrm{PW}[\mathrm{CIF}(N)] = \left(\sum_{i=1}^{p} p_{si} E_{PVsi}\right) \frac{K_{p_s}(1-K_{p_s}^N)}{1-K_{ps}} + \left(\sum_{i=1}^{p} p_{gi} E_{PVgi}\right) \frac{K_{p_g}(1-K_{pg}^N)}{1-K_{pg}} \quad (12)$$

This analysis is focused in the Spanish territory, where the net-metering law is still in a draft stage, so the PV electricity injected to the grid it is not regulated in economic terms (neither in bureaucratic nor technical terms), in other words, the energy not used at the moment, is given, free of charge, to the electricity company, therefore the Eq. (12) is simplified as there is no remunerations or economic savings (in electricity bonus) from the user's standpoint. This simplification is shown in Eq. (13)

$$\mathrm{PW}[\mathrm{CIF}(N)] = \left(\sum_{i=1}^{p} p_{si} E_{PVsi}\right) \frac{K_{p_s}(1-K_{p_s}^N)}{1-K_{ps}} \quad (13)$$

Nevertheless, according to the net-metering and self-consumption draft that may be approved before this paper is published, we have included in the results section, a small profitability analysis where we have considered the worst scenario possible: the absence of any remuneration for the energy excess injected to the grid, and the addition of a back-up toll fee that the user has to pay to the company for the energy that it is self-consumed.

The discounted payback time (DPBT) is the required number of years (N=PB) that satisfies the following:

$$PW[\mathrm{CIF}(\mathrm{PB})] \geq \mathrm{LCC}_{USP} \quad (14)$$

For the calculation of the Internal Rate of Return (IRR), which stands for the value of d that makes NPV=0, it can be expressed using a rearrangement of Eqs. (5) and (8):

$$0 = \mathrm{PW}[\mathrm{CIF}(N)] - \mathrm{LCC}_{USP} \quad (15)$$

It is important to clarify that if the parameters involved in the calculation of IRR in Eq. (15) have been considered in current currency, nominal IRR is obtained ($\mathrm{IRR}_{nominal}$). On the other hand, if these parameters have been considered in constant currency, without the inflation, the value that it is obtained is IRR_{real}. Besides, the net internal rate of return (IRR_n) is derived from the IRR by the relation $\mathrm{IRR} = \mathrm{IRR}_n + \mathrm{WACC}$.

3.1. Estimation of parameters

A summary of the parameters used in the previous equations is shown in Table 10. It has been included some of the data used in the energy and cost analysis with the aim to facilitate the comprehension of the table.

Regarding the unitary prices per kWh of self-consumed PV electricity (p_{si}), they have been defined according to the price contracted freely between the University and the supplier. As it was shown in Table 1, there are different prices (P1–P6) for each period defined in the Spanish law mentioned.

It is difficult to foresee the behavior of the electricity markets. However, it seems that the rising trend of energy consumption, mainly due to the emerging economies, will make the world's energy demand increases. This fact, together with the increase of oil prices, will push up electricity rates [54]. In this paper ε_{ps} is set higher than the annual inflation rate (g) and the annual increase rate of the PV electricity unitary price (ε_{ps}) has been supposed to be 5%. The discount rate (d) is assumed equal to the WACC in order to calculate the NPV and DPBT. In our case the WACC is 5.6%.

Table 10
Parameters considered in the profitability analysis.

Location	Factors							Financial			g (%)	d_g (%)
	$[PV_{IN}]_{kWp}$ (€ kWp^{-1})	PV power (kWp)	Annual yield (kWh kWp^{-1})	p_{si} € kWh^{-1} (including 21% of taxes)	ε_{ps} (%)	PV_{OM} (€/years)	ε_{PVOM} (%)	Low-interest loan (80% of PV_{IN})		Own capital (20% of PV_{IN})		
								i_l (%)	N_l (years)	d_l (%)		
Building 1	1900	101	1418									
S. Parking lot 1	1700	110										
S. Parking lot 2	1700	110	1239	P1=0.16720087								
S. Parking lot 3	1700	110		P2=0.13652223								
Building 2	1900	91	1418	P3=0.106787								
N. Parking lot 1	1700	100		P4=0.080577								
N. Parking lot 2	1700	100	1237	P5=0.097498	5	1% $[PV_{IN}]$	2.8	6	15	5	2.8	0.8
N. Parking lot 3	1700	100		P6=0.071927								
N. Parking lot 4	1700	98										
Pergola	1800	110	1291									
Building 3	1900	74	1418									
N–W Parking lot	1700	105	1240									

Table 11
Economic analysis summary.

Location	$IRR_{nominal}$ (%)	IRR_{real} (%)	IRR_{net} (%)	NPV (€)	DPBT (years)
Building 1	8.82	5.86	3.16	77995	17
S Parking lot 1 S Parking lot 2 S Parking lot 3	8.50	5.55	2.83	67637	17.5
Building 2	8.82	5.86	3.16	70272	17
N Parking lot 1 N Parking lot 2 N Parking lot 3 N Parking lot 4	8.48	5.53	2.82	61044 59824	17.5
Pergola	8.83	5.38	2.67	67058	18
Building 3	8.82	5.86	3.16	57144	17
N-W Parking lot	8.51	5.56	2.84	64792	17.5

3.2. Profitability results and sensitivity analysis.

The results obtained in the profitability analysis for each PV potential location are shown in Table 11, where there is gathered information about the main profitability indexes.

The results obtained in this economic analysis recommend the implementation of PVGCS for several reasons. First of all, the internal rate of return ranges from 8.48% to 8.83%. Secondly, in the base case proposed, the net present value is always positive, and the discounted payback time ranges from 17.5 to 18 years.

Although the results obtained are favorable, it is necessary to undertake a sensitivity analysis with different scenarios depending on the variations of those three profitability indexes. It is complicated to estimate the evolution of the financial parameters because the present economic situation is unpredictable, so the sensitivity analysis has been done based on the scenarios that appear when it is considered variations of $\pm$25% in the initial investment cost and in the PV electricity yield.

The return of the investment in number of years will tend to improve because the initial investment cost is very unlikely to increase in a 25%. In this scenario, the DPBT can decrease down to 12 years, so the expectations are very favorable (see Fig. 14). If the analysis is done considering the energy yield that depends on the radiation data used, different Spanish location or meteorological cycles, there is a pronounced variation when the estimation of the energy yield decreases in a 25%. In this case (see Fig. 15), the DBPT is around line of 25 years, so the systems proposed may be not so feasibility.

The variation in the NPV in the same range of sensitivity reveals that an increase in the initial investment cost reflects a worsening in the NPV, but like the previous index, the most critical aspect is the decrease in the energy collected. In this case, the NPV appears to be negative in almost every PV system proposed, except for those locations perfectly oriented and tilted, but anyway, the NPV in those PV systems is not suitable (Figs. 16 and 17).

Lastly, the IRR variations in Figs. 18 and 19 show that in the range proposed for the initial investment cost, all the cases seem to be profitable, although when it is considered an increase of a 25% in the cost per kWp (very improbable), the results are close to the profitability limit. Nevertheless, the IRR index, like the other ones, is very sensitive to variations in the energy generated. In these cases under the 25% decrease scenario the IRR is lower than the WACC, so it can be said that in these situations, the owner of the PV systems is losing money.

According to the fluctuating electricity price market, and with the aim of increasing the utility of this work, we have done an

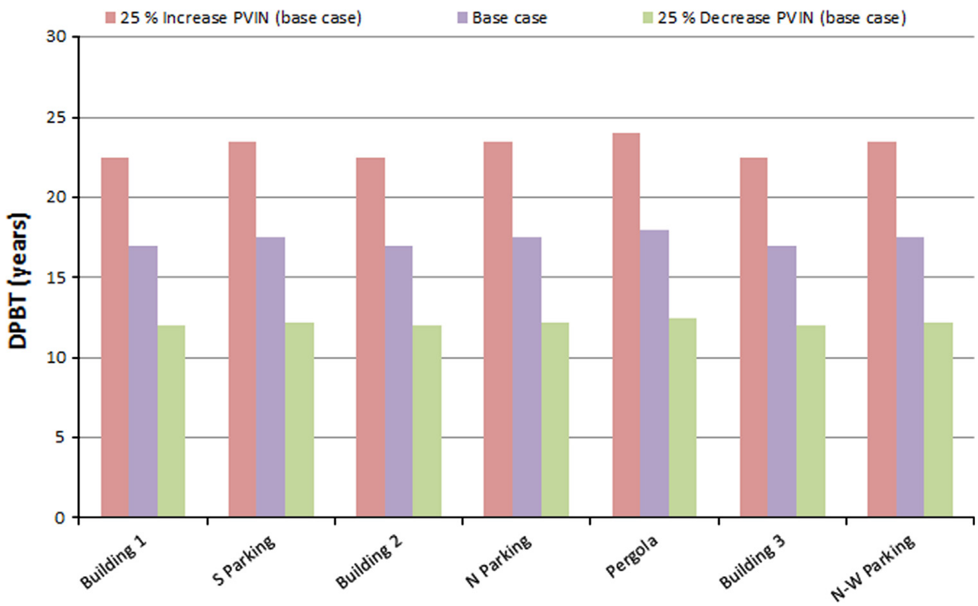

Fig. 14. DPBT sensitivity analysis regarding the initial investment cost variations.

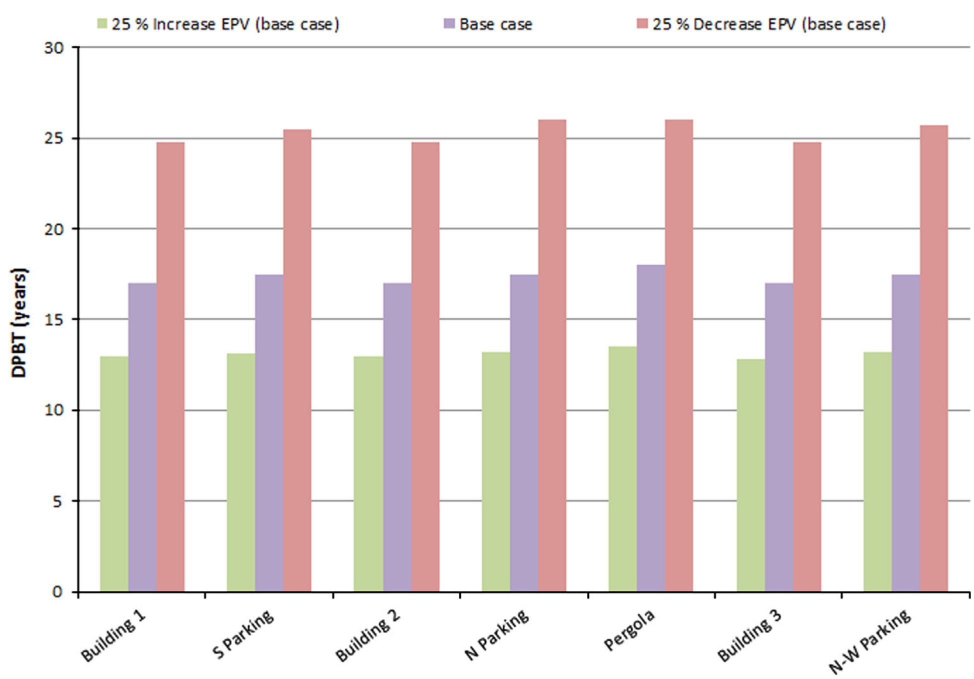

Fig. 15. DPBT sensitivity analysis regarding the PV electricity yield variations.

additional sensitivity analysis, where it has planned a scenario where the electricity tariffs can vary up to a 30% increase or down to a 30% decrease. This issue can be useful not only in Spain, but also this analysis can be extrapolated to other countries with significantly differences in the tariff applied.

Figs. 20–22 show that the higher the increment in the PV electricity unitary price, the better is the improvement in the DPBT, NPV and IRR indexes. The worst scenarios can be observed when the prices decrement down to 20% or 30%, where in most of the cases proposed, the systems are no longer profitable. Obviously, if the user receives less money for the energy saved or self-consumed, it will be harder to recover the investment done. Fortunately, the present trend in the Spanish Electrical tariffs is in ascending order.

3.2.1. Other possible scenarios—additional taxes

The constantly changes in the Spanish legislation makes that any study in this area may become obsolete or no valid enough if there are not considered additional taxes or fees that the Government may introduce for renewable energy systems.

Under this context, another sensitive analysis was carried out considering an arbitrary tax that may be applicable to renewable energy or self-consumption systems for having the right to connect to the grid. Obviously, this taxation will have consequences in the indexes calculated previously. In this section a sensitivity analysis of the IRR, NPV and DPBT have been made considering a tax coefficient δ, which values vary in the range of 0% up to 30%. This coefficient has been applied to the saved cash inflow from the PVGCS, once the asset amortization and the

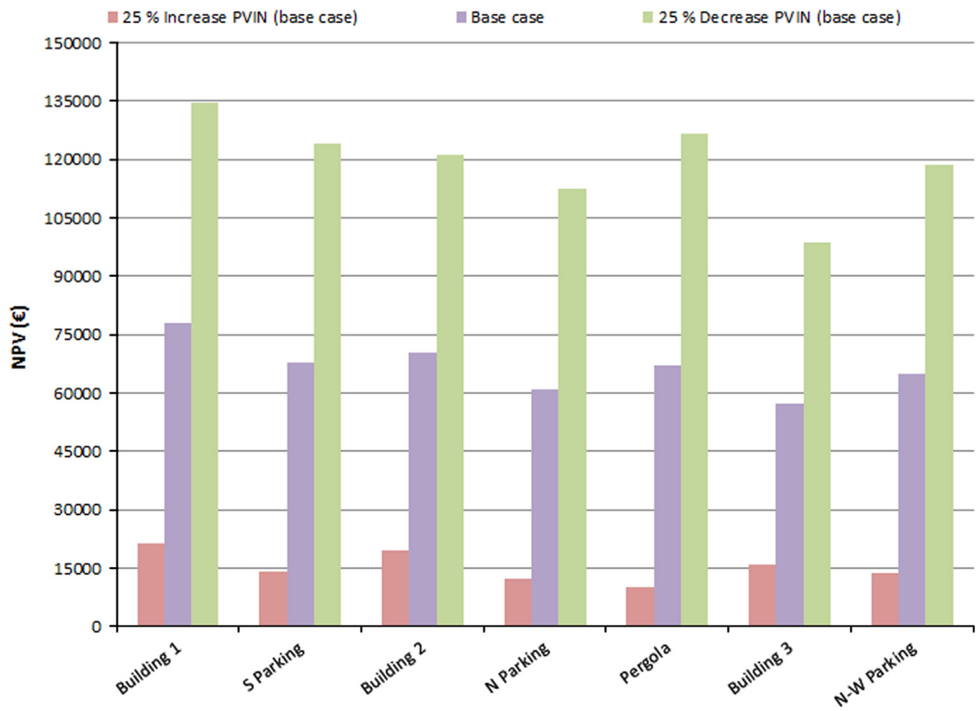

Fig. 16. NPV sensitivity analysis regarding the initial investment cost variations.

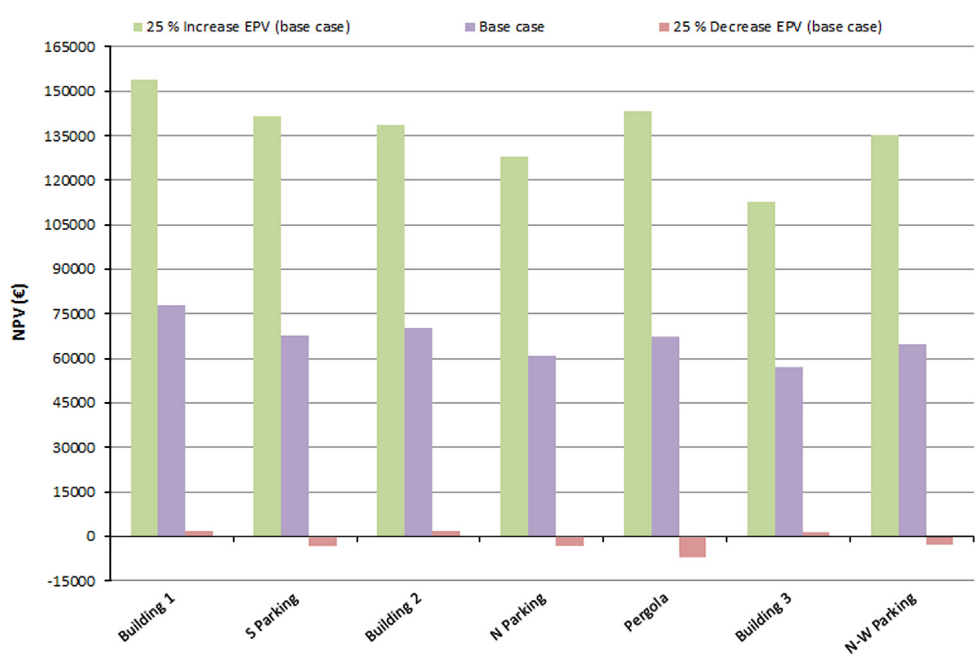

Fig. 17. NPV sensitivity analysis regarding the PV electricity yield variations.

operation and maintenance cost of the PVGCS are deducted. The asset amortization has been considered lineal over the life cycle of the PVGCS and it has been excluded from taxation. The results of the analysis in Building 1 are shown in Figs. 23–25, corresponding to the DPBT, NPV and IRR respectively.

Another issue that should be targeted is related with a draft of a Royal Decree that the Spanish Government has recently published, which establishes the bureaucratic, technical and economic conditions that the power supply with self-consumption must accomplish. In this scenario, the Government has introduced a controversial extra fee per kWh self-consumed within the consumer´s network.

During a transitional period, the back-up toll fee that should be applied to the University, corresponding to the tariff 6.1, is shown in Table 12. Under this new scenario, all the economic analysis has been redone including this possible new back-up toll fee and considering the same consumption-generation profiles of the potential PV systems and the periods of the University electrical tariff. A summary of the results can be observed in the Table 13, where in all the cases the indexes worsen as it was expected.

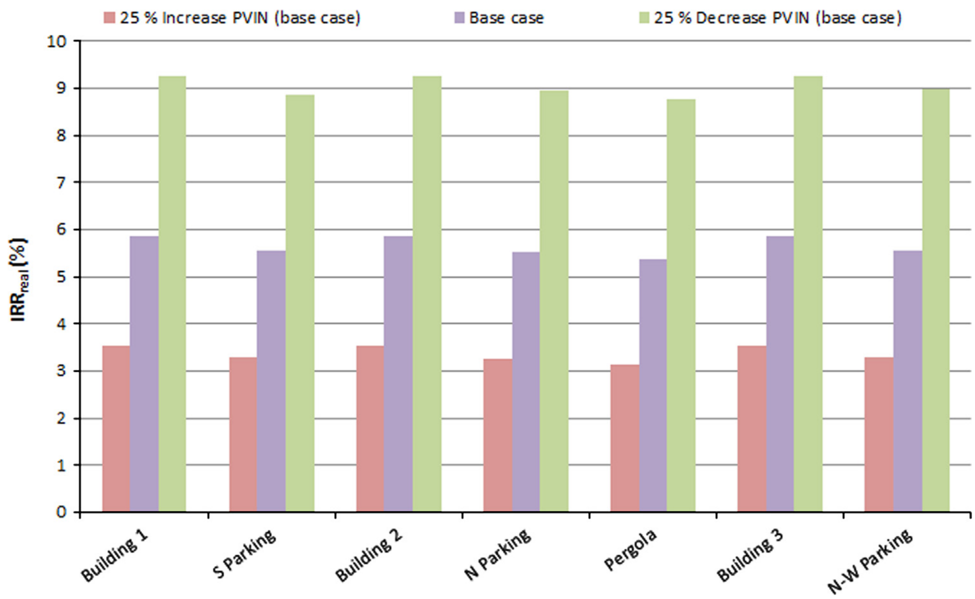

Fig. 18. IRR sensitivity analysis regarding the initial investment cost variations.

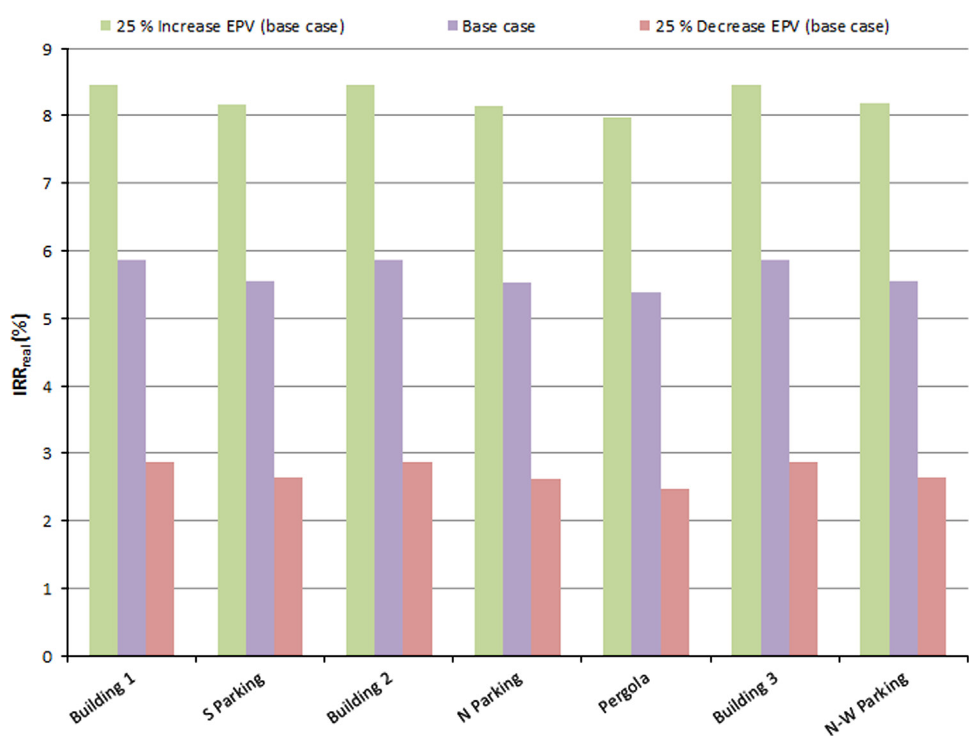

Fig. 19. IRR sensitivity analysis regarding the PV electricity yield variations.

4. Conclusions

At the end of 2011 Spain had installed a cumulative PV power of more than 4,400 MW, which means that the present PV contribution to the electricity demand is around 3% [55]. It can be assessed that this technology is mature enough to compete against other sources of energy. Nevertheless, if this technology is expected to reach the power estimations of the Spanish Renewable Energy Plan, where more than 5,900 MW of accumulative power is planned to be installed by 2015 [56], it is necessary to find other economic alternatives, moreover when all the incentives or subsidies have been cut-off.

The energy yield calculated, typical of sunny regions such as the South of Europe, and the lowering of PV system prices, give coherence to the results obtained in the cost and profitability analysis, where the data obtained proof that, under the scenarios studied and in most of the cases proposed in the sensitivity analysis, these sort of renewable energy systems are feasible and profitable, but it is also necessary a strong support from the Government.

It is important to highlight, from the user's standpoint, that the aim of these systems is not only a business idea, but it is a way to be responsible of your own energy consumption too. It is like having the possibility to have your own farm, but in solar terms.

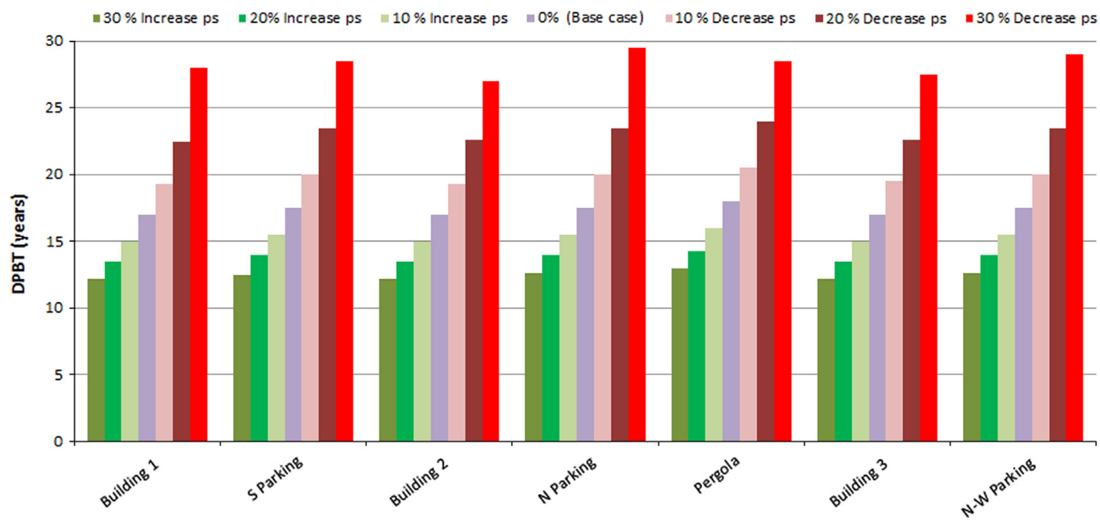

Fig. 20. DPBT sensitivity analysis regarding PV electricity unitary price (p_s) variations.

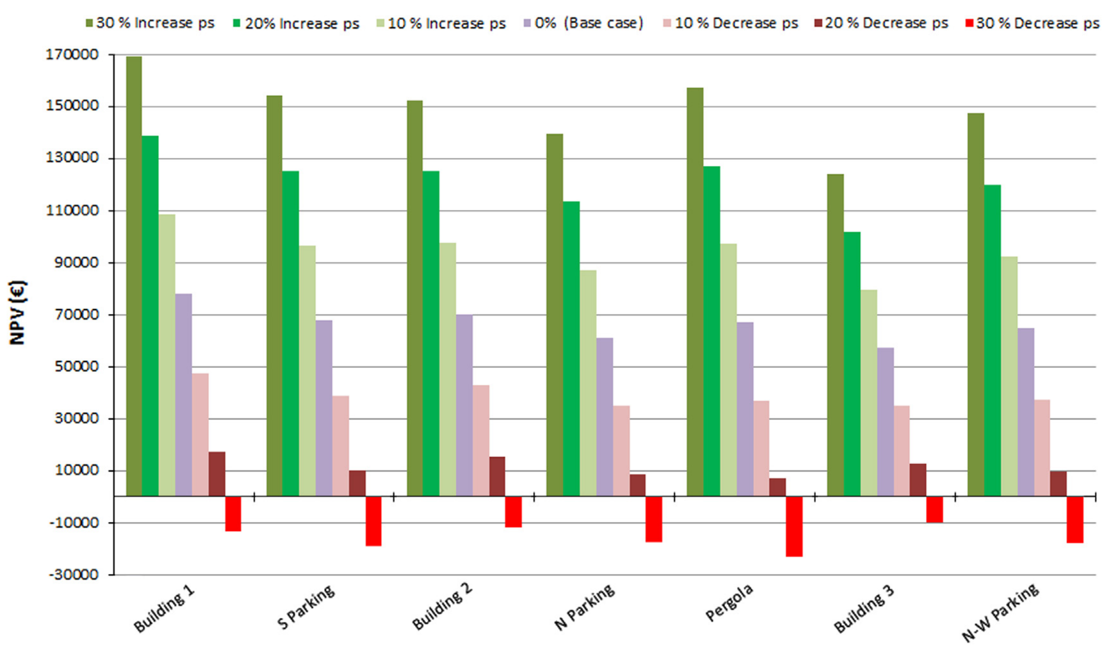

Fig. 21. NPV sensitivity analysis regarding PV electricity unitary price (p_s) variations.

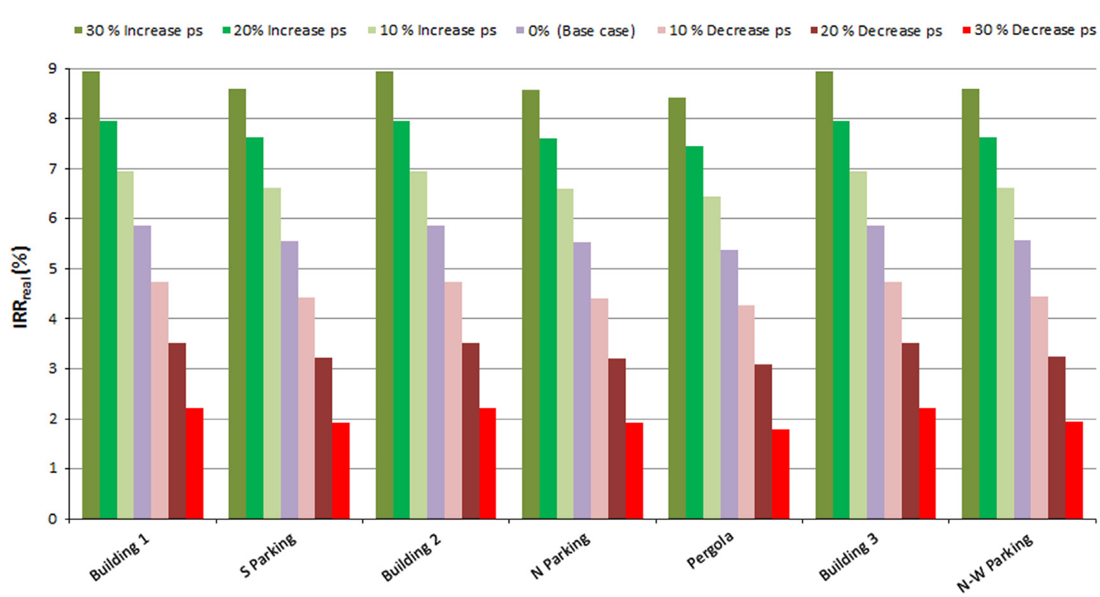

Fig. 22. IRR sensitivity analysis regarding PV electricity unitary price (p_s) variations.

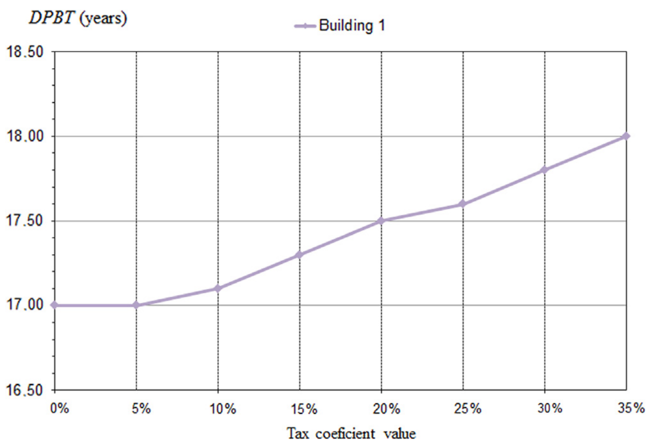

Fig. 23. DPBT sensitivity analysis on building 1 regarding a tax increment.

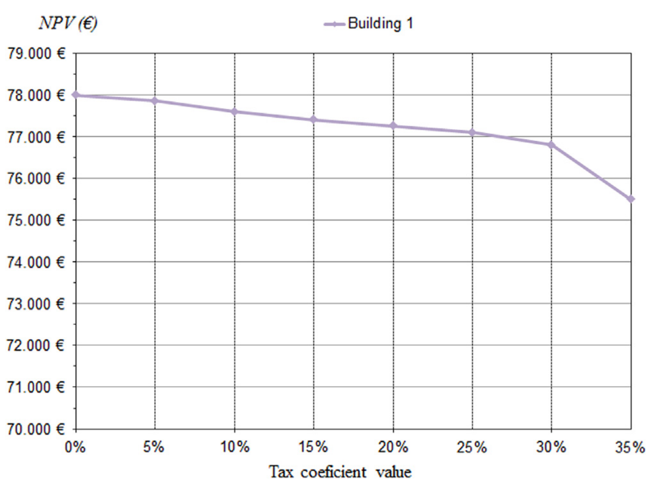

Fig. 24. NPV sensitivity analysis on building 1 regarding a tax increment.

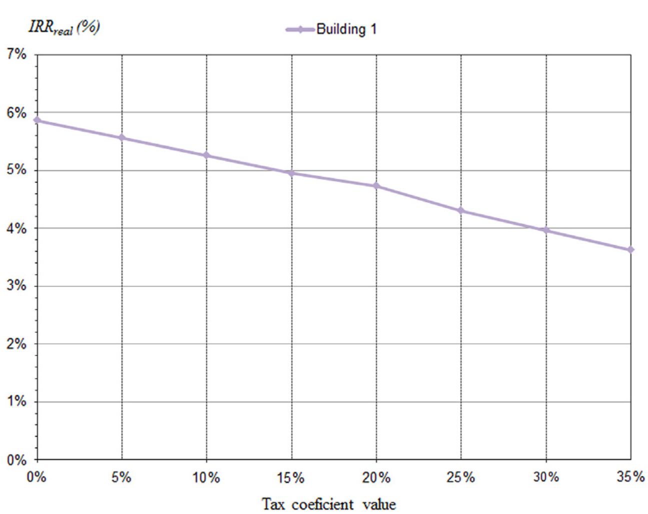

Fig. 25. IRR sensitivity analysis on building 1 regarding a tax increment.

Table 12
Back-up Toll proposed for the tariff 6.1 in the Royal Decree draft.

Price periods	Back-up toll fee (€ kWh^{-1})
P1	0.044149
P2	0.030248
P3	0.019107
P4	0.012878
P5	0.011060
P6	0.006676

Table 13
Economic analysis summary, including a back-up toll fee.

Location	$IRR_{nominal}$ (%)	IRR_{real} (%)	IRR_{net} (%)	NPV (€)	DPBT (years)
Building 1	6.84	3.93	1.18	27,653	21.5
S Parking lot 1 S Parking lot 2 S Parking lot 3	6.56	3.66	0.89	20,164	22
Building 2	6.85	3.94	1.18	24,850	21.5
N Parking lot 1 N Parking lot 2 N Parking lot 3 N Parking lot 4	6.55	3.64	0.88	17,968 17,608	22
Pergola	6.40	3.51	0.74	17,492	22.5
Building 3	6.86	3.94	1.19	20,301	21.5
N–W Parking lot	6.57	3.67	0.90	19,421	22

Table 14
Economic analysis summary for different price scenarios.

Location	Tariffs January 2013	Tariffs August 2013	Tariffs under the Royal Decree draft (with self-consumption back-up toll)
	IRR_{real} (%)	IRR_{real} (%)	IRR_{real} (%)
Building 1	8.92	5.86	3.93
S Parking lot 1 S Parking lot 2 S Parking lot 3	8.58	5.55	3.66
Building 2	8.92	5.86	3.94
N Parking lot 1 N Parking lot 2 N Parking lot 3 N Parking lot 4	8.56	5.53	3.64
Pergola	8.40	5.38	3.51
Building 3	8.92	5.86	3.94
N–W Parking lot	8.59	5.56	3.67

The only thing that is missing is a stronger regulatory support from the government and a decrease in the reticence from the main electric companies, but the reality approved in the last laws in Spain is headed to the opposite direction.

If the electrical market keeps on increasing the electrical tariffs and the Government adding extra fees for the Renewable energies, the profitability of the PV technology would decrease down to a critical level, and maybe hardly to recover in the short-mid-term. As an example of this conclusion, Table 14 shows the decrease of the IRR in the last year in Spain related to the decrease in the electrical tariff from January 2013 to August 2013. This decrease in the profitability was explained in the sensitivity analysis carried out in Fig. 22 and it is also hard to control and predict. Where it is outstanding the decrease in the IRR is under the situation of the inclusion of a possible back-up toll fee, which can artificially turn a profitable system, with no feed-in tariff or subsidy, into a non-interesting solution for the Spanish Energy deficit.

Nevertheless, nowadays in the Spanish news, the possibility of a new increase in the energy tariff is a trending topic [57], so for

the photovoltaic market this is good evidence that this technology may still be profitable in Spain. It would be also interesting to extent this study to similar cases in other European countries with different economic scenarios.

Acknowledgment

This work was partially supported by the University of Jaén within the frame of the "UNIVERSOL" Project. Additionally, The Center of Advanced Studies in Energy and Environment has also been involved in the research presented in this paper and some parts of this work has been partially carried out thanks to the College Teacher Training Program (Formación de Profesorado Universitario) of the Spanish Ministry of Education.

Appendix A. Terminology

d	nominal discount rate (%)
d_i	dividends rate (annual retribution rate for own capital) (%)
DPBT	discounted payback time (years)
d_r	real discount rate (%)
E_{PVg}	annual PV yield injected into the grid by the user (kWh)
E_{PVs}	annual PV yield self-consumed or saved by the user (kWh)
g	annual inflation rate (%)
$G(\alpha,\beta)$	effective irradiance within the PV generator surface (W m^{-2})
$H_{dm}(0)$	monthly average value of horizontal daily global radiation (Wh m^{-2})
$H_{dr}(0)$	horizontal global radiation (Wh m^{-2})
i_l	annual loan interest
IRR	internal rate of return
IRR$_n$	net internal rate of return
LCC$_{USP}$	life-cycle cost of the PVGCS from the user's standpoint (€)
LCOE	levelised cost of electricity (€ kWh^{-1})
N	useful life of the PVGCS (years)
N_l	time duration of the loan (years)
NOCT	nominal operation cell temperature (°C)
NPV	net present value (€)
p	tariff periods
p_g	PV–electricity unitary price into to the grid paid by the user (€ kWh^{-1})
P_M	maximum power (W)
$P_{M,STC}$	maximum power at standard test conditions (W)
p_s	PV–electricity unitary price self-consumed or saved by the user (€ kWh^{-1})
PV_{AOM}	annual operation and maintenance cost of the PVGCS (€)
PV_{IN}	initial investment cost on the PVGCS (€)
PV_{IS}	initial investment subsidy (€)
PV_{OC}	own capital (is the portion of the initial investment financed with own capital) (€)
PW [CIF(N)]	present worth of the cash inflows from a PVGCS through its useful life (€)
PW[PV$_{OM}$]	present worth of the PVGCS operation and maintenance cost (€)
PW[PV$_{IN}$]	present worth of the user's initial investment cost on the PVGCS (€)
T_{aMdm}	monthly average value of the maximum daily ambient temperature (°C)
T_{amdm}	monthly average value of the minimum daily ambient temperature (°C)
T_{aMdr}	maximum ambient temperature of the representative day (°C)
T_{amdr}	minimum ambient temperature of the representative day (°C)
T_c	cell temperature
WACC	weighted average cost of capital (%)
γ	power temperature coefficient (°C^{-1})
ε_{pg}	annual increase rate of the electricity price injected to the grid paid by the user (%)
ε_{pl}	annual decrease rate of the power of the PVGCS (%).
ε_{ps}	annual increase rate of the electricity price self-consumed or saved by the user (%)
ε_{PVOM}	annual escalation rate of the operation and maintenance cost of the PVGCS (%)

References

[1] David Pérez, Víctor Cervantes, M. Jesús Báez, Jaime González-Puelles. PV grid parity monitor. ECLAREON S.L. Available online from: ⟨http://www.eclareon.eu/en/gpm⟩; October 2012 [accessed December 2012].

[2] Lettner G., Auer H. Economic conditions to achieving the dynamic PV grid-parity in the residential sector in different European Countries. In: Proceedings of the 12th IAEE European energy conference on "energy challenge and environmental sustainability". Ca'Foscari University of Venice(I). Available online from: ⟨http://www.webmeets.com/files/papers/AIEE/2012/152/Lettner abstract.pdf⟩; 2012 [accessed December 2013].

[3] del Río Pablo. Ten years of renewable electricity policies in Spain: an analysis of successive feed-in tariff reforms. Energy Policy 2008;36:2917–29.

[4] Garbe K, Latour M, Michele Sonvilla P. Reduction of bureaucratic barriers for successful PV deployment in Europe. Final report. PV LEGAL. Available online from: ⟨http://www.pvlegal.eu/en/results/status-reports.html#c461⟩; February 2012 [accessed December 2012].

[5] Ministry of Industry, Tourism and Trade. Royal Decree 1699/2011. Boletín Oficial del Estado. Number 295, section 1. Spain. p. 130033. Available online from: ⟨http://www.boe.es/boe/dias/2011/12/08/pdfs/BOE-A-2011-19242.pdf⟩; December 8, 2011 [accessed December 2012].

[6] Head of the State. Royal Decree-Law 1/2012. Boletín Oficial del Estado. Number 24, section 1. Spain. p. 8068. Available online from: ⟨http://www.boe.es/boe/dias/2012/01/28/pdfs/BOE-A-2012-1310.pdf⟩; January 28, 2012 [accessed December 2012].

[7] Comisión Nacional de Energía. Informe sobre la propuesta de real decreto por el que se establece la regulación de las condiciones administrativas, técnicas y económicas de la modalidad de suministro de energía eléctrica con balance neto. Available online from: ⟨http://www.cne.es/cne/doc/publicaciones/cne09_12.pdf⟩; March 2012 [accessed December 2012].

[8] Royal Decree Draft. Propuesta del Proyecto de Real Decreto por el que se establece la regulación de las condiciones administrativas, técnicas y económicas de las modalidades de suministro de energía eléctrica con autoconsumo y de producción con autoconsumo. Madrid: Ministerio de Industria, Turismo y Comercio. Available online from: ⟨http://www.suelosolar.es/newsolares/newsol.asp?id=8479⟩; July 2013 [accessed December 2013].

[9] Mir-Artigues Pere. The Spanish regulation of the photovoltaic demand-side generation. Energy Policy 2013;63:664–73.

[10] del Río Pablo, Mir-Artigues Pere. Support for solar PV deployment in Spain: some policy lessons. Renew Sustain Energy Rev 2012;16:5557–66.

[11] Ciarreta Aitor, Gutiérrez-Hita Carlos, Nasirov Shahriyar. Renewable energy sources in the Spanish electricity market: instruments and effects. Renew Sustain Energy Rev 2011;15:2510–9.

[12] Spertino Filippo, Di Leo Paolo, Cocina Valeria. Economic analysis of investment in the rooftop photovoltaic systems: a long-term research in the two main markets. Renew Sustain Energy Rev 2013;28:531–40.

[13] Antonio Colmenar-Santos Severo, Campíñez-Romero Clara. Pérez-Molina and Manuel Castro-Gil. Profitability analysis of grid-connected photovoltaic facilities for household electricity self-sufficiency. Energy Policy 2012;51:749–64.

[14] Ministry of Industry, Energy and Tourism. Resolution from September 24, 2013. Boletín Oficial del Estado. Number 235. Spain, p. 79087. Available online from: ⟨http://www.boe.es/boe/dias/2013/10/01/pdfs/BOE-A-2013-10146.pdf⟩; October 1, 2013 [accessed December 2013].

[15] Ministry of Industry, Energy and Tourism. Orden IET/1491/2013 from August 1st. Boletín Oficial del Estado. Number 185. Spain. p. 56729. Available online from: ⟨https://www.boe.es/boe/dias/2013/08/03/pdfs/BOE-A-2013-8561.pdf⟩; August 3, 2013 [accessed December 2013].

[16] Ministry of Industry, Tourism and Trade. Orden ITC/2794/2007 from September 27. Boletín Oficial del Estado. Number 234 Spain. p. 39690. Available online

from: ⟨http://www.boe.es/boe/dias/2007/09/29/pdfs/A39690-39698.pdf⟩; September 29, 2007 [accessed December 2012].
[17] Branker K, Pathak MJM, Pearce JM. A review of solar photovoltaic levelized cost of electricity. Renew Sustain Energy Rev 2011;15:4470–82.
[18] Clastres Cédric. Smart grids: another step towards competition, energy security and climate change objectives. Energy Policy 2011;39:5399–408.
[19] Vincenzo Giordano, Alexis Meletiou, Catalin Felix Covrig, Anna Mengolini, Mircea Ardelean, Gianluca Fulli, et al. Smart Grid projects in Europe: lessons learned and current development (2012 update). JRC scientific and policy reports; 2013.
[20] Ortega MJ, de la Casa J, Almonacid G, et al. Large-Scale deployment of photovoltaic systems in building integration: "Universol Project". In: Proceedings of the 25th European PVSEC. Valencia, Spain; September 2010.
[21] Ortega MJ, de la Casa J, Almonacid G, Talavera DL, Muñoz E, Martínez Ruíz A, et al. UNIVERSOL project. Final results. In: Proceedings of the 26th European PVSEC. Hamburg, Germany; September 2011.
[22] Talavera DL, Muñoz-Cerón E, de la Casa J, Ortega MJ, Almonacid, G. Energy and economic analysis for large-scale integration of small photovoltaic systems in buildings: the case of a public location in Southern Spain. Renew Sustain Energy Rev 2011;15:4310–9.
[23] Iqbal. M. An introduction to solar radiation. Toronto: Academic Press; 1983.
[24] Lorenzo E Electricidad solar. Progensa, Sevilla; 1994.
[25] Perpiñan O, Lorenzo E, Castro MA. On the complexity of radiation models for PV energy production calculation. Solar Energy 2007;15(3):265–74, http://dx.doi.org/10.1016/j.solner.2007.06.07.
[26] NASA. Surface meteorology and solar energy data set. Available online from: ⟨http://www//eosweb.larc.nasa.gov/sse/⟩ [accessed October 2012].
[27] Liu BYH, Jordan RC. The interrelationship and characteristic distribution of direct, diffuse and total solar radiation. Solar Energy 1960;4(3):1–19.
[28] Page JK. The estimation of monthly mean values of daily total short-wave radiation on vertial and inclined surfaces from sunshine records for latitudes 40°N–40°S. In: Proceedings of the Annual Meeting, American Section of the International Solar Energy Society. Denver, Colorado 1979.
[29] Whillier A. The determination of hourly values of total solar radiation from daily summations. Arch Meteorol Geophys Bioklimatol Ser B 1956;7(2):197–204.
[30] Perez R, et al. A new simplified version of the Perez diffuse irradiance model for tilted surfaces. Solar Energy 1987;39(3):221–31.
[31] Martin N, Ruiz. JM. Annual angular reflection losses in PV modules. Prog Photovolt Res Appl 2005;13.
[32] Lorenzo. E. Radiación solar y dispositivos fotovoltaicos. Progensa 2006;2:167–96.
[33] Osterwald CR. Translation of device performance measurements to reference conditions. Solar Cells 1986;18(3–4):269–79.
[34] Fuentes M. Contribución al modelado del comportamiento eléctrico a sol real de módulos fotovoltaicos de silicio cristalino y CIS. Doctoral thesis. University of Jaen. May 2009.
[35] Drif M, Pérez PJ, Aguilera J, Almonacid G, Gómez P, de-laCasa J. UNIVER project. A grid connected photovoltaic system of 200 kWp at Jaén University. Overview and performance analysis. Sol Energy Mater Sol Cells 2007;91:670–83.
[36] Pérez PJ, et al. Operating experience of photovoltaic systems installed at the University of Jaen. Int J Energy Environ 2010;4(4):189–96.
[37] Short W, Packey DJ, Holt T. A manual for the economic evaluation of energy efficiency and renewable energy technologies. Golden, Colorado: NREL; 1995 (NREL/TP-462-5173).
[38] Talavera DL, Nofuentes G, de la Casa J, Aguilera J. Sensitivity analysis on some profitability indices for photovoltaic grid–connected systems on buildings: the case of two top photovoltaic European areas. J Sol Energy Eng 2013;135 011003-1–011003-11.
[39] EurObserv'ER. Photovoltaic barometer. Available online from: ⟨http://www.eurobserv-er.org/pdf/photovoltaic_2012.pdf⟩; April 2012. [accessed December 2012].
[40] International Renewable Energy Agency. Renewable energy technologies: cost analysis series. solar photovoltaics. Power Sector 2012(4/5): ([accessed December 2012].).
[41] International Energy Agency. Trends in photovoltaic applications survey report of selected IEA countries between 1992 and 2006. Report IEA-PVPS T1-16:2007. 01/08/2007. Available online from: ⟨http://www.iea-pvps.org/index.php?id=92⟩ [accessed December 2012].
[42] International Energy Agency. Trends in photovoltaic applications survey report of selected IEA countries between 1992 and 2007. Report IEA-PVPS T1-17:2008. Available online from: ⟨http://www.iea-pvps.org/index.php?id=92⟩ [accessed December 2012].
[43] International Energy Agency. Trends in photovoltaic applications survey report of selected IEA countries between 1992 and 2008. Report IEA-PVPS T1-18:2009. 01/08/2009. Available online from: ⟨http://www.iea-pvps.org/index.php?id=92⟩ [accessed December 2012].
[44] International Energy Agency. Trends in photovoltaic applications survey report of selected IEA countries between 1992 and 2009. Report IEA-PVPS T1-19:2010. 01/10/2010. Available online from: ⟨http://www.iea-pvps.org/index.php?id=92⟩ [accessed December 2012].
[45] International Energy Agency. Trends in photovoltaic applications survey report of selected IEA countries between 1992 and 2010. Report IEA-PVPS T1-20:2011. 09/11/2011. Available online from: ⟨http://www.iea-pvps.org/index.php?id=92⟩ [accessed December 2012].
[46] International Energy Agency. Trends in photovoltaic applications survey report of selected IEA countries between 1992 and 2011. Report IEA-PVPS T1-21:2012. 19/09/2012. Available online from: ⟨http://www.iea-pvps.org/index.php?id=92⟩[accessed December 2012].
[47] Asociación de la Industria Fotovoltaica. Hacia el crecimiento sostenido de la fotovoltaica en España. Informe annual 2011. Spain. Available online from: ⟨http://www//unef.es/descargas/?did=790⟩; June 2011. [accessed December 2012].
[48] European Central Bank. Statistics poket book. Available online from: ⟨http://www.ecb.int/pub/pdf/stapobo/spb201210en.pdf⟩; October 2012. [accessed October 2012].
[49] Bank of Spain. Economic indices. Available online from: ⟨http://www.bde.es/webbde/es/estadis/infoest/e0903.pdf⟩ [accessed December 2012].
[50] Bank of Spain. Economic indices. Available online from: ⟨http://www.bde.es/webbde/es/estadis/infoest/e0502.pdf⟩ [accessed December 2012].
[51] Danchev S, Maniatis G, Tsakanikas A. Returns on investment in electricity producing photovoltaic systems under de-escalating feed-in tariffs: the case of Greece. Renew Sustain Energy Rev 2010;14:500–5.
[52] Dirk C, Jordan, Kurtz Sarah R. Photovoltaic degradation risk. National Renewable Energy Laboratory, presented at the 2012 World Renewable Energy Forum Denver, Colorado May 13–17, 2012 ([accessed December 2012]).
[53] Talavera DL, Nofuentes G, Aguilera J. The internal rate of return of photovoltaic grid-connected systems: a comprehensive sensitivity analysis. Renew Energy 2010;35:101–11.
[54] International Energy Agency. Oil market report, annual statistical supplement for 2011. p. 29–36. Available on line from: ⟨http://www//omrpublic.iea.org/omrarchive/sup2011.pdf⟩ [accessed October 2012].
[55] European Photovoltaic Industry Association (EPIA). Global market outlook for photovoltaics until 2016. Available online from: ⟨http://www.epia.org/news/publications/⟩; May 2012 [accessed December 2012].
[56] Ministry of Industry, Tourism and Trade. Spanish Government. Plan de Acción Nacional de Energías Renovables de España (PANER) 2011–2020. Available online from: ⟨http://www.minetur.gob.es/energia/desarrollo/EnergiaRenovable/Paginas/paner.aspx⟩; June 2010 [accessed December 2012].
[57] Víctor Martínez. Temor entre las multinacionales a una nueva subida de la luz. Diario El Mundo. Available online from: ⟨http://www.elmundo.es/economia/2013/12/06/52a0fb9a61fd3d91708b457a.html⟩ [accessed December 2013].